The Journal

OF THE

Royal Aeronautical Society

A Monthly Illustrated Magazine devoted to all subjects connected with the Navigation of the Air.

EDITED FOR THE

COUNCIL OF THE ROYAL AËRONAUTICAL SOCIETY

BY

J. LAURENCE PRITCHARD, Hon. Fellow.

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Edited for the Council by J. LAURENCE PRITCHARD, Fellow

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NOTICES

Journal

Members will notice that several changes have been made in the present issue of the Journal. In the first place the Council feel that the title, "Aeronautical Journal," did not sufficiently indicate that it is the official publication of the Society, and it has therefore been decided to alter it to "The Journal of the Royal Aeronautical Society," which has the advantage of retaining the characteristic of the old title. There have been at the same time certain changes made in the type and *format* of the Journal to bring it more into line with other similar scientific and technical journals.

Election of Members

The following members were elected at a meeting of the Council held on December 19th:—

Associate Fellow.—A.A.S.El. Kirdany.
Students.—H. J. Penrose and H. Sommer.

International Air Congress, London, 1923

An International Air Congress will be held in London from June 25th to 30th, under the auspices of the Air Ministry, the Royal Aeronautical Society, the Royal Aero Club, the Air League and the Society of British Aircraft Constructors. H.R.H. the Duke of York has agreed to become President and Lord Weir Vice-President of the Congress and the Duke of Sutherland (Under-Secretary of State for Air) is Chairman of the Main Committee. The Society's representatives on the Committee are Lieut.-Colonel O'Gorman (who is one of the Vice-Chairmen), Professor Bairstow, Mr. Griffith Brewer and Lieut.-Colonel A. Ogilvie. The Secretary of the Society has been appointed General Secretary, and the Society has been entrusted with the organisation and administration of the Congress, which has its offices at 7, Albemarle Street.

Students' Section

The following programme of papers for Students' Meetings has been arranged for the remainder of the Session:—

1923.

Jan. 25.—"Discussion on English and German Methods of Estimating Aeroplane Performance," F. Radcliffe, B.Sc. Chairman, Mr. Harris Booth.

Feb. 8.—(Title to be announced later) W. L. Le Page.

,, 22.—"The High Lift Wing," T. A. Kirkup. Chairman, Major Gnosspelius.

Mar. 8.—"Air Transport," J. D. Campbell.

,, 22.—(Title to be announced later) S. H. Evans.

XIIM

Library

The following books have been received and placed in the Library:—"Practical Applications of X-Rays," by C. W. C. Kaye; "Les Hélicoptères," by W. Margoulis; "Mechanical Testing," by Batson and Hyde; "Discoveries and Inventions of the Twentieth Century," by E. Cressy; "Technological Papers of the Bureau of Standards," No. 211, by the Department of Commerce, Washington, D.C.; "Fatigue of Metals," by Professor C. E. Stromeyer; "A Bundle of Meteorological Paradoxes," by W. J. Humphries (Smithsonian Institution); "Rhythm in Nature," by F. W. Flattely (Smithsonian Institution); and "Who's Who in Engineering."

Arrangements for the Month

Jan. 4, 5.30 p.m.—Royal Society of Arts. Professor Junkers, "Metal Aeroplanes."

,, 10, 3.0 p.m.—Society's Library. Adjourned Technical Discussion.

,, 11, 3.0 p.m.—Royal Society of Arts. *Juvenile Lecture.* Mr. R. A. Frazer, "Model Aircraft."

,, 18, 5.30 p.m.—Royal Society of Arts. Major J. D. Rennie, "Flying Boats."

,, 25, 7.0 p.m.—*Students' Section.* Society's Library. F. Radcliffe, "English and German Methods of Estimating Aeroplane Performance."

W. Lockwood Marsh, *Secretary.*

PROCEEDINGS

Second Meeting, 59th Session

An Ordinary General Meeting was held at the Royal United Service Institution on Thursday, October 19th, Prof. Bairstow, Chairman, in the chair.

The Chairman, in introducing the lecturer, Mr. J. D. North, said he was connected with one of the leading aeroplane design firms in the country, a firm which, mainly through the activities of Mr. North and his colleagues, had established a position as leading thinkers among the designers of the country. The case that Mr. North was dealing with in his lecture was rather a difficult one, and no doubt part of the strength of the argument that would be put forward came from Mr. North's belief in the subject. At the same time, Mr. North hoped to put before the meeting reasons for believing that in the immediate future metal construction could be a really serious competitor to the older wood construction or a composite construction of wood and metal. There was a good deal of material in the paper, and he hoped that many people would take part in the discussion and bring out the points of what was an extremely interesting subject.

THE CASE FOR METAL CONSTRUCTION

BY JOHN D. NORTH, FELLOW.

Although I have been requested by the Council of this Society to read a paper on the metal construction of aeroplanes, there are two phases of the subject with which I do not feel prepared to deal. In the first instance, any paper dealing historically with this matter is likely to give rise to controversy which is of neither scientific nor engineering interest, and I propose to leave this aspect severely alone. Secondly, I do not pretend to expound a process of design. The technique of this new branch of the engineering art is still too fluid; while so far as experimental results are concerned it is probable that more have been published than have been digested.

The aeroplane engineer, designer, constructor or user, not unnaturally, is inclined to pin his faith to the system of composite construction, which, brought to a state of high perfection, he has found to serve him well in the past. All the history of engineering relates the gradual displacement of timber by lighter and more durable structures of steel, but such a transition in aeroplanes he feels is difficult, if not impossible, to realise with advantage. Of the three separate metal aeroplane movements in Great Britain, Germany and France, that in this country, at least, received its principal impulse, not from a realisation of the great engineering advantages attending it, but from the pressure of a world shortage of the limited supplies of that class of timber most suitable for light structural purposes.

The cessation of the demand for the mass production of aircraft, coincident with the termination of hostilities, deprived the movement of its principal motive power, but not before it had been realised in some quarters that metal, and particularly steel, construction, could succeed on its own merits even in competition with a normal timber supply.

It may be helpful first to note some general criticisms of metal construction.

The principal argument which has been advanced is that metal construction has not demonstrated its advantages over the usual composite form of

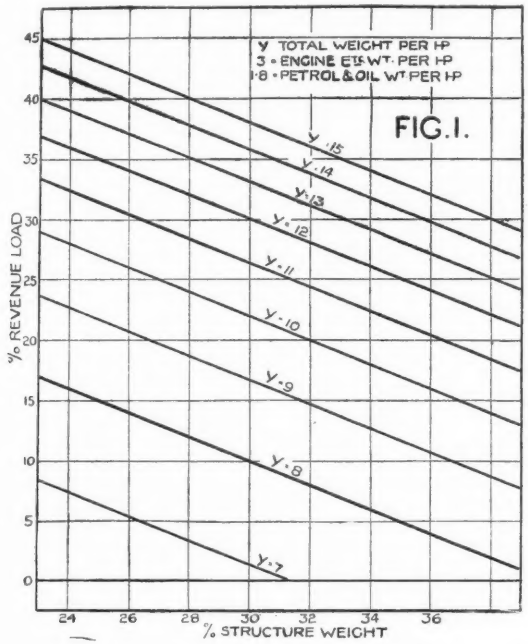
structure. This is not, strictly speaking, a sound criticism, being in the nature of an *argumentum ad ignorantiam*, and though it is quite true that in most cases the users of this argument have not had the necessary experience of metal construction to enable them to appreciate it, such an argument cannot be considered as conclusive. It may be inferred from various remarks that in the opinion of critics metal construction is expensive, perhaps heavier and in temperate climates at least not likely to be more durable than wood. It has further been criticised by analogy on the grounds that small motor boats are invariably, or at least most successfully, constructed of timber, and in some cases it has been further put forward that metal construction must be associated with large aircraft just as it is associated with large ships. The weakness of this argument is immediately apparent when we consider that the first object of a boat is to keep out water, and the adverse experience of constructors of steel motor boats is almost entirely due to the fact that it is difficult to make them water-tight. These conditions are not analogous to those obtaining in aircraft, and it hardly seems necessary to pursue the argument further. With regard to the other criticisms, I hope to indicate in these notes that the following advantages may be obtained by the use of metal construction :—

(1) Retrenchment of weight.
(2) Improvement in the reliability of materials.
(3) A longer life, particularly under conditions of storage.
(4) A better resistance to adverse climatical conditions.
(5) An improvement in bulk manufacturing facilities.
(6) A reduction in some risks and effects of fire.

It is, I think, not always sufficiently realised what a very important effect comparatively small differences in the structure weight of an aeroplane have upon its general characteristics; particularly is this the case when the aeroplane is designed for a high performance or a very long range of flight. There has been some little tendency, and designers of equipment seem to be special offenders in this respect, to imagine that a few pounds here and a few there are negligible in regard to the gross weight of the aeroplane, and that special efforts to economise weight are therefore not necessary. If it is realised that the margin available for military load per unit h.p. is only the remainder after deducting the structure, the engine, installation and fuel weights, it will be appreciated that a saving in weight in an individual part is reflected in an economy on the gross weight, greater by the ratio of the gross weight to the military or revenue load. This is illustrated in Fig. 1, which shows the variation of revenue load —the revenue load in this instance includes pilot, instruments, equipment, etc., so that the influence of structure weight on revenue load is enhanced, particularly in the case of small aeroplanes—or military load with different percentages of structure weight for aeroplanes having various classes of performance. The variations in performance have been indicated by the power loading in lbs. per h.p., since this figure conveys in a simple manner the typical performance, to the aeronautical engineer. It will be noticed that even with a power loading of 15, which is representative of most modern commercial aeroplanes, a reduction of structure weight from 34 per cent. to 26 per cent. increases the revenue load from 34 per cent. to 42 per cent., an increase of nearly 25 per cent. in the utility of the aeroplane. In the case of the high performance aeroplane, the increase will be seen to be vastly greater, and in many cases makes possible a type of aeroplane which will be placed out of court with the heavier structure weight. I have every reason to believe that the structure weight of aircraft can be reduced from an average of 33 per cent. to an average of 25 per cent. to 27 per cent. by the use of metal construction, an advantage which while extremely beneficial for commercial aeroplanes, is absolutely imperative in the case of military machines. I do not suggest that the whole of this gain can be obtained at once, but theoretical considerations and practical experience both indicate that

there is a reasonable probability of arriving at such a figure at no very distant date, provided experiment on broad lines is continued unhampered by the necessity of obtaining immediate results from experimental expenditure.

Let us consider how this retrenchment of weight is to be accomplished. It can be shown from first principles that it is possible to make structural members of metal considerably lighter than of timber, and this has been borne out by practical experience. There are two physical properties of structural materials which are of first order of importance in considering the weight of the structure manufactured from them. Firstly, the ratio of the modulus of elasticity to the specific gravity, and secondly, the manner in which this ratio falls off with increase of stress intensity. This latter property is generally considered by focussing the attention upon the yield point of the material at which



in the ordinary normalised carbon steels, a critical change in the value of E occurs. In the case of timber, which is a vegetable growth itself of complex structure, it is only possible to discuss the change of elasticity with stress in reference to a similar critical case, and indeed since the cause of failure in light compression members of wood and metal is somewhat dissimilar, the difficulty of an exact comparison is enhanced. A table* summarises the elastic moduli of a number of materials, either most commonly used in aircraft construction or by reason of their properties most suitable. In the second column of the table these values have been made specific by dividing them by the specific gravity of the material, and from this it will be seen that in the case of these materials there is very little to choose between them though metal is at some advantage.

If we were to imagine that the structure of an aeroplane were composed entirely of " Euler " struts, in which the modulus of elasticity would be the only

* This table will be printed in the February issue.

property of the material of importance, it would be apparent that that form of construction, which would give us members with the greatest radii of gyration, would give us the lightest structure. The second table furnishes the critical stress which will be obtained in the outer compression fibres of a strut or a beam, at failure. This stress is again made specific by dividing by the specific gravity of the material, and in this case it is found that there are marked differences between the various types of material showing an advantage for certain of the light alloys over timber, and of certain classes of steels over both. If an aeroplane were constructed entirely of short struts failing in pure compression and of ties failing in pure tension, it is obvious that, supposing the other physical properties of the material to be suitable, the greatest advantage could be obtained by using the material having the highest critical stress, so far as compression failures were concerned, and the highest ultimate stress so far as the tension members were concerned. These maxima are usually to be found in the same material. In making these statements, it is postulated that the design of the member is such as to enable the critical stress to be realised. In other words, for the purpose of our argument, this stress is the critical stress by definition, and the circumstances under which it can be realised will be discussed later. We can now consider the properties of the materials in a more general way.

Fig. 2 shows the ratio of the intensity of load to the free length/radius of gyration of struts manufactured from materials of different critical stress. This figure will be familiar to most as representative of the characteristic curves of Mr. Southwell and Prof. Robertson. The first inspection of this figure will show that in order to realise the advantage of materials having a high critical stress, it is necessary that the ratio of l/k should be kept as low as possible.

It is at this point that the principal structural characteristic of the aeroplane exercises an important influence. The aeroplane is a very large structure for its weight, which means that struts with a low l/k must have very thin walls where they are made of dense material such as steel, or in a lesser degree, aluminium and its alloys.

It is a well-known experimental fact that, where the thickness of the wall is small compared with the radius of curvature and the length of the arc, the intensity of load indicated in Fig. 2 is not realised owing to the crinkling or buckling of the shell at a stress less than that which has been assumed as the critical stress. The lightest strut, therefore, will be that one in which the compromise between low l/k and high critical stress is best effected.

An attack on this problem of local instability by rigid analytical methods is outside the scope of mathematical processes to-day, at least so far as the complex forms demanded for engineering reasons and indicated by experimental results are concerned. At the same time the elastic properties of those materials (*e.g.*, cold worked steels and hardened and tempered alloy steels) which are most suitable, are far removed from the simple proportionality necessarily assumed in elasticity problems. In spite of this we can obtain valuable guidance by reference to two simple cases for which mathematical solutions have been obtained. I do not mean that because the cases are relatively simple compared with those of the actual structural members which we are discussing that the problems are simple ones. Any one can disabuse his mind of this idea by looking up the references.

Case (*a*).—A flat rectangular plate loaded uniformly in its plane and supported at its edges.

Case (*b*).—A uniformly loaded circular tube.

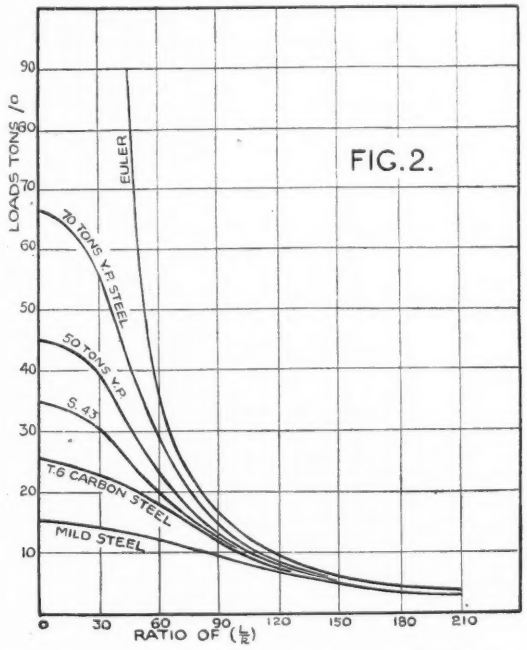
(*a*) A method of obtaining this result, first discovered by Prof. G. H. Brian, is given in " The Mathematical Theory of Elasticity," by Prof. A. E. H. Love, on p. 540 of the third edition. A flat rectangular plate of thickness $2h$, and of

sides $2a$ and $2b$, is assumed supported freely at its edges against motion perpendicular to its plane, and subject to uniform compressive loads P_1 and P_2 per unit length of edge.

Assuming perfect elasticity, in a state of neutral equilibrium the plate can distort by displacements perpendicular to its plane into a series of double sine waves, provided the following relationship holds:—

$$P_1 (m^2/a^2) + P_2 (n^2/b^2) = 1/4\, D\pi^2 (m^2/a^2 + n^2/b^2)^2$$

In the above m and n are integers expressing the number of half waves into which the lengths $2a$ and $2b$ are divided respectively, and are those which give the lowest values for P_1 and P_2. D is the "flexural rigidity" of the plate and is equal to $2Eh^3/3(1-\sigma^2)$, where E is Young's modulus and σ is Poisson's ratio for the material.



For our purpose we consider an infinite flat strip of thickness t, and of breadth B, freely supported along its edges and loaded parallel to its length only by a uniform compressive stress of intensity p.

Let the half wave length in the longitudinal direction be l. Then in the above equation:—

$$\begin{aligned} 2a/m &= l \\ 2b &= B \\ P_1 &= p \,.\, t \\ P_2 &= 0 \\ 2h &= t \\ D &= Et^3/12(1-\sigma^2) \end{aligned}$$

$$\text{and } p \,.\, t \times 4/l^2 = Et^3\pi^2/48(1-\sigma^2)(4/l^2 + 4n^2/B^2)^2$$

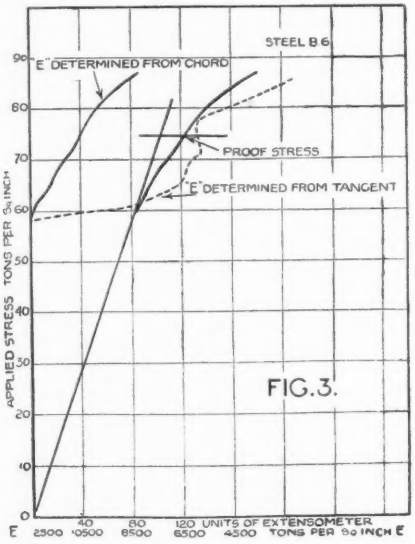
For a minimum $n = l$ and $l = B$, giving:—$p = \pi^2/3(1-\sigma^2) \times Et^2/B^2$.

The constant term in this expression is of limited practical value, but the result is important as indicating the manner in which the variables involved are to be taken into account.

(*b*) This case is examined fully by Mr. R. V. Southwell in his paper on "The General Theory of Elastic Stability" (Phil. Trans. Roy. Soc. Ser. A., Vol. 213). It is sufficient for our purpose to note that the critical stress in a tube of radius R for all forms of failure is proportional to $E\,t/R$.

These results and a consideration of the general theory of thin shells indicate the factors governing the intensity of stress at which instability will occur.

Firstly this stress is proportional to the value of E. In those classes of steels where there is a well-defined yield point shortly after the limit of proportionality is reached the meaning of this is very simple. At the yield point E "collapses" and so does the shell. Provided thickness/(radius of curvature) is above a certain figure its value has practically no influence on the stress at which instability occurs. But with cold worked and hardened and tempered materials the

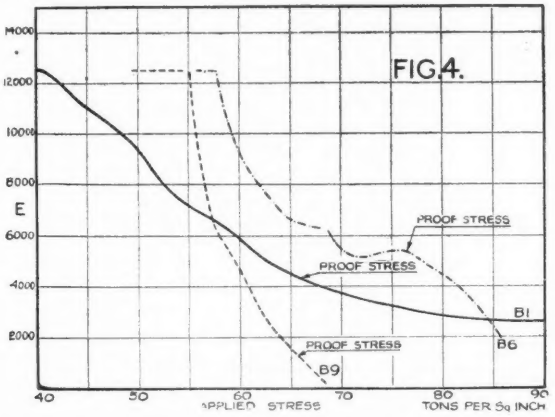


case is different. The limit of proportionality may be very low, and the rate of change of curvature of the stress strain curve is very slow. An endeavour has been made to define some structurally important stress to meet this difficulty, and the result of these efforts is incorporated in the B.E.S.A. specifications S40 and S43 under the term "proof" stress, which is defined as follows.

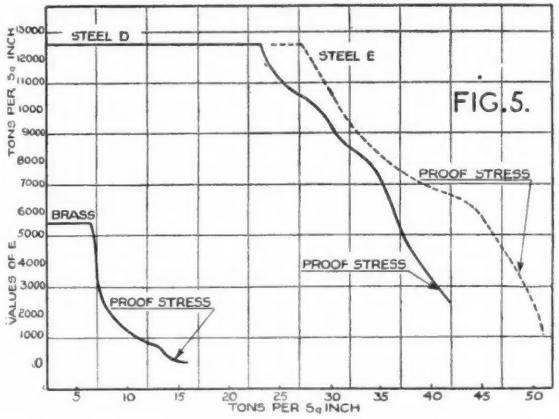
The proof stress is the greatest load per square inch which, when applied to the test piece for 15 seconds and removed, produces a permanent extension of not more than 0.1 per cent. of the gauge length. The proof stress shall be determined upon a test piece having a gauge length of exactly 4in. When a stress of 40 tons per sq. in. is applied to the specimen, and maintained, the total temporary extension of the gauge length must not be greater than 0.017in., and when a stress of 50 tons per sq. in. is applied to the specimen and maintained, the total extension of the gauge length while under load must not be less than 0.020in.

It has been customary for some time to identify this stress with the maximum realisable in a thin walled structure, however small the curvature might be with respect to the thickness of the shell and the "free" length of the arc. From considerations already indicated this is not correct, and indeed "proof" stress

can only have a significant bearing on the stress at which failure by crinkling will occur if the slope of the stress-strain curve of a given material is always constant at the proof stress. This opens up what is, I believe, a new method of examining the structural properties of a material, namely, by a consideration of its elastic properties over the whole of its stress range. The term "elastic"



is used here in the same loose sense that "E" has been used for the slope of the stress-strain curve beyond the limits of proportionality and into the region of plastic deformation. So far as the immediate problem is concerned, although it is of some importance whether the extension is elastic or plastic, there are good grounds for believing that the limit of proportionality is not, in all classes of steel, necessarily the dividing line between these two states. The alternative



to the loose use of these terms is either unnecessary verbosity or a "specially invented terminology," and I feel that laxity is the least of the three evils, and that there is little danger of being misunderstood.

I suggest that the physical properties of a material, *so far as the "critical" stress in a thin-walled member is concerned*, are best represented by the first differential of the stress strain curve with respect to stress. Fig. 3 shows such a curve, together with the stress-strain curve from which it is derived, for a

nickel-chrome steel hardened and tempered at 300 C. There are obvious difficulties in preparing such a curve where the mechanical errors of graphical differentiation are superimposed on the inevitable inaccuracies of strain measurement, but the broad significance of such a method of presentation may be appreciated by a reference to Fig. 4, where the "elasticity-stress" curves are given on a more convenient scale for three nickel-chrome steel specimens (A) fully hardened, (B) hardened and tempered at 300 C., (C) hardened and tempered at 500 C. (B) is taken from Fig. 3.

Fig. 5 gives the same curves for the following material:—

Steel D—Coldworked steel blued at 100 deg. C.
Steel E—Coldworked stainless iron (not blued).
Brass—Muntz metal (cold-drawn).

PROOF STRESS.

Steel	B.9	65.75 tons per sq. in.	E. 1,300 tons per sq. in.	
,,	B.6	76.5 ,, ,,	E. 5,400 ,, ,,	,,
,,	B.1	66.25 ,, ,,	E. 4,300 ,, ,,	,,
,,	E.	48.5 ,, ,,	E. 3,600 ,, ,,	,,
,,	D.	40.75 ,, ,,	E. 2,900 ,, ,,	,,
Brass		14.75 ,, ,,	E. 100 ,, ,,	,,

From this it will be seen that there is no simply defined critical stress, and that by varying the curvature to the thickness and the *free* arc length we can push further along the curve with lower values of E and higher "critical stress."

It is clear that there would be serious difficulties in verifying commercially these elastic properties of a metal, but this is an aspect of the case to which I will return later, when discussing inspection and testing.

As regards the influence of the form of the wall or shell on the critical stress, the significant features are the curvature of the arc, its *free* length and the thickness. Experimental results within my experience indicate that other things being equal (including the value of E), the critical stress is proportional to the thickness as foreshadowed by a general consideration of the theory of thin shells, but in dealing with the question of form, the difficulty lies in the *free* length of the arc. The problem is analogous to that of a redundant structure in which the members are not pin-jointed, and is hopelessly complicated by sectional deformations and the variations of E.

Apart from these difficulties we have those relating the fibre stresses to the external forces on the member. It is convenient to represent the fibre stresses, as deduced from experimental evidence of load and deflection, as $P/A + Pd/Z$ for direct compression loads, and as $P/A + Pd/Z + BM/Z$ where there are external shear loads, where:—

P = end load.
A = area.
BM = bending moment.
Z = section modulus.
d = deflection.

The usefulness of these expressions in ordinary engineering should not blind us to the limitations imposed by the assumptions on which they are based, all of which are violated in the structures we are considering. It is perhaps not too much to say that they have no *real* meaning and that the "stress" calculated can only justifiably be used for estimating the loads which members of similar form will sustain within limits of the ratio of shear to end load permitted by the extent of the experimental evidence. To interpret this stress as representing the *actual conditions* governing the local failure of the shell is dangerous and misleading.

In determining the deflection, and in consequence the stress, in a laterally loaded strut in which the stress induced is beyond the limit of proportionality, the

variation of " E " must be considered differently. In this case the actual stress for an assumed given strain instead of the increase of stress for a hypothetical small increase of strain, is required, and therefore E is determined by the slope of the chord from the zero of the stress strain diagram to the appropriate point of the curve instead of by that of the tangent at the appropriate point. In the calculation a trial and error method must be used with an assumed value of E, and a further uncertainty is introduced by the fact that all points of the member are not equally stressed. Experiment has verified the obvious conclusion that the effective E for calculating the deflection lies somewhere between the " chord " value for the maximum stress and the maximum value, but it is not possible at present to give any more definite information, since the experimental " mean " value of E deduced from measurements of deflection is influenced by distortions not taken account of by the simple beam theory. The " chord " value of E for the steel B.6 is plotted against stress in Fig. 3.

All this may seem rather hopeless, from the scientific point of view perhaps it is, but let us consider the whole process by which a structural member of an aeroplane is designed.

Firstly, the conditions of flight for which the aeroplane is to be designed. These are fixed by an Order in Council and are interpreted by a series of good round numbers delivered after much labour by a committee. Over the manner of arriving at these numbers a decent veil is cast which it would be unwise to disturb. But the Committee seems to know its job in so far as the aircraft are not abnormally heavy nor do they collapse in the air. These numbers are converted to external forces in a particular manner founded on precedent, supported by very doubtful aerodynamic data and also fortified by the same Order in Council. The loads in the members are then estimated by ignoring those members to take account of whose presence would seriously complicate the calculations and by making what are often the wildest assumptions as to the nature of the joints between the members. This brings us to that very data which we were regretting our inability to interpret in an accurate scientific manner. But the whole process works after a fashion because aeroplanes are not designed by science, but by art in spite of some pretence and humbug to the contrary. I do not mean to suggest for one moment that engineering can do without science, on the contrary, it stands on scientific foundations, but there is a big gap between scientific research and the engineering product which has to be bridged by the art of the engineer.

Nevertheless, the technique of the design of thin metal members is progressing rapidly. To arrive analytically by measuring the frictional coefficient of the cloth, the resilience of the balls and cushions, at the precise way to play a complicated stroke at billiards is practically hopeless, but practice and a knowledge of principles deduced from scientific analysis of simple cases will produce surprising results. So it is that, over a wide range, light metal members can be designed with every confidence that they will fulfil their designer's expectations and realise the advantages in weight economy foreshadowed by the properties of the materials.

Inspection and Manufacture

It would be perhaps too much to say of light metal construction that the material is half the battle, but there would be a strong element of truth in such an assertion. I am not suggesting that there is one particular class of steel or light alloy which will be found to be ideal for all purposes. On the contrary, I believe that the types of material used in a single metal aeroplane will increase as time goes on. What we require are materials that can be produced with the necessary degree of uniformity both as regards their elastic properties in the sense these have already been discussed and as regards their plasticity, both absolute as ductility, and in relation to the *true* elastic properties. This last is required to be reasonably uniform in the state in which the strip is to be worked

(sections formed from strip and riveted together are the most characteristic forms of light metal construction). The strip in forming through rolls or dies springs back from the profile of the tool by an amount dependent on its resilience. Reasonable limits are thus required if tools are to produce a satisfactorily uniform article. Control at present is limited to an upper and lower " proof " stress and a bend test. These tests, comparatively simple as they appear, seem somewhat to strain the capacities of commercial testing and inspection without giving as much information as is required.

What is wanted is a stress/strain diagram from which the properties of the materials can be deduced, and it is unfortunate that there is no machine capable of producing them commercially and reliably. For that matter there is not even a standard extensometer which is commercially practical. It is possible that this class of testing apparatus may be improved in the near future. There is also the alternative that research may show a connection between these elastic properties and some more easily measured feature of the material. It is a matter well worth the attention of metallurgists, testing engineers and physicists generally.

A further mechanical uniformity in strip is required in thickness, flatness and straightness. The tolerances laid down in the B.E.S.A. specifications seem satisfactory and more than a slight departure from them often leads to manufacturing troubles.

The problem of manufacture from the strip onwards has two phases which are novel and of special importance. Firstly, forming the strip. Secondly, riveting it.

There is a simple formula for designing tools for forming strip. It is " live and learn." Direct attack on the resilience problem is probably hopeless, but one soon arrives at a few general principles of design, though when marked departure from experience comes along it often brings rude shocks in its train. There are broadly three methods of forming strip—rolling, drawing and pressing—and all have their uses and limitations; but whatever method is used (all are really required), it is necessary to get the best results, to have machines of special design, and my own experience is that it is most satisfactory to design and make them on the spot.

The commonest process in aircraft work is to form the strip in its final state of treatment, but although this has great advantages in assisting production by eliminating heat treatment processes, I believe that a certain amount of soft forming with subsequent heat treatment or even hot forming will be in regular use, by reason of the wider scope of materials and forms opened up. With satisfactory tools and uniform material the production of formed sections makes little demand on skilled labour and can easily be brought to a large production standard.

Riveting is a problem less easily tackled, it is so indefinite. The number of rivets in a steel aeroplane runs into many tens of thousands, the cost of riveting and all it implies is probably the critical factor in the cost of production, and the profit and loss scale will be turned by the drawing office and the planning department. This phase of technique is being slowly and painfully developed, and it is here to a large extent that the high cost of development appears. Metal construction is not inherently expensive. All our experience of the manufacture of details where the technique is in an advanced state confirms this. Money is spent on mistakes and errors of judgment, trial and error the foundation stones of experience.

Corrosion

The question " What about corrosion?" is such a common one that I may perhaps be excused if I introduce a little resumé of present-day opinions on corrosion generally. I hope to show that the susceptibilities of steel aeroplane parts to corrosion are due to faulty shop practice rather than any other cause and to

suggest that with proper precautions there is little to fear from oxidation. Further, the aeroplane which is virtually incorrodible is at last a practical proposition and will make its appearance in the near future. A survey of the large volume of experimental data which has been accumulated on the subject of the corrosion of iron and steel leads us, at an early point in the inquiry, to the conclusion that the chemical reactions involved are by no means simple. Something more than a direct oxidation of iron atoms is involved. This is not in the least surprising. Of almost any apparently simple chemical reaction it can be said that the more closely we look into the mechanism of such change the more complex it grows.

It will not be disputed that the more that is known of the onset and course of development of a disease the greater hope there is, not only of effecting a cure, but of preventing a recrudescence.

Three theories which have been put forward to account for the corrosion of iron and steel will be noticed briefly :—

1. The acid theory.
2. The electro-chemical theory.
3. The recent colloid theory of Dr. Friend.

It may be said at once that no one of them above will suffice to explain all the well-established experimental facts.

1 *The Acid Theory*

This requires the necessary presence of some acid in the water in contact with the metal before iron will rust at all. The carbonic acid present in water in all ordinary cases suffices. It is probably not a fact that iron will not rust in the absence of an acid. Be that as it may, in all cases that interest us the acid, carbonic, is inevitably present, and the presence of any acid, even so weak a one as carbonic, undoubtedly accelerates the corrosion of iron.

2 *The Electro-Chemical Theory*

In its broadest interpretation, includes the acid theory. This theory requires that, for corrosion, the iron shall be in contact with an electrolyte and oxygen. It is impossible and, for our purposes, unnecessary to say whether chemically pure water is an electrolyte; impossible because it is inconceivable that chemical methods have reached the ultimate in refinement, the chemically purest water yet prepared has a definitely measurable electrical conductivity and is an electrolyte in consequence; unnecessary, because the only water that interests us, that which condenses when the temperature falls below the dew point, that which falls as rain, is an undoubted electrolyte, and contains a measurable, though small, concentration of hydrogen and hydroxyl ions. The chemist associates what he calls acid properties with the presence, in large or small concentration, of the hydrogen ion. So water is an acid, a weak acid, perhaps the weakest known.

We have, in materials like iron and steel, which are neither pure nor homogeneous, a very fertile field for the establishment, in contact with an electrolyte, of local voltaic couples, and if the iron, as must sometimes occur, be anodic in such a couple, into solution it will tend to go as the iron ion, with a driving electromotive force behind it, which depends on the nature of the electrolyte in contact with it and on the nature of the cathode. Now this state of affairs, with iron the anode in a voltaic couple, will be found only in places on the surface of any given specimen. Corrosion due to this cause will then only develop at certain well-marked points of attack, accounting thus for the familiar phenomenon of pitting.

But this voltaic action, due to the heterogeneous character of the material and resulting in pitting, is not all. There has to be considered, in addition, the action between the metal itself and the electrolyte with which it is in contact. A

metal in contact with a liquid ionises to some extent, with a definite electromotive force which can be measured tending to ionise it. In the absence of disturbing factors a state of equilibrium is set up when further ionisation ceases and a definite difference of potential between metal and solvent exists. This is the ionic theory of solutions universally accepted by physical chemists as giving the best expression yet to the whole of their knowledge of the mechanism of solution. The disturbing factor that matters to us is the presence of other ions in the liquid, hydrogen ions. The electro-chemical theory of corrosion then attributes the corrosion of the metal to two causes, operating together or singly.

(1) Local voltaic actions.
(2) Straightforward solution of the metal.

The non-corrodible steel will be of such a character that neither of these causes can operate.

Dealing with local voltaic actions first. The presence or absence of the conditions necessary for setting up such actions will depend upon :—

First and foremost, the presence of impurities or, what is equally harmful, local segregations. As an example, it has been established that in the presence of black scale the iron becomes anodic and consequently passes into solution.

(2) *The micro-structure* of the material and anything which has happened to the material in its life history which is known to affect the micro-structure—*e.g.*, heat treatment—is very important.

(3) *Chemical composition.*

(4) *The physical condition of the material*, due to heat treatment or mechanical working. Strained and unstrained portions of a homogeneous material constitute an active voltaic couple.

There is nothing here that proper care in the selection, manufacture and handling of the material cannot successfully deal with.

Straightforward Solution of the Metal.—Whether or not a metal goes into solution in a liquid, it has been said above, depends upon what potential difference exists in the particular case under investigation. All these quantities are susceptible of accurate measurement. Hadfield and Newberry, working on these lines, in acid solutions, have shown that before solution of a given metal can take place the following condition must be satisfied :—

Electrode potential of the metal + the over-voltage must be greater than the hydrogen potential for the solvent.

The electrode potential or solution pressure is a matter of chemical composition ; and it should not be impossible to produce an alloy to fulfil this condition, in which corrosion by straightforward solution would be impossible.

Of the two causes of corrosion, according to the electro-chemical theory, the localised formation of voltaic couples, resulting in pitting, appears to be responsible for most of the damage. Recent experiments carried out at the United States Bureau of Standards on the corrosion of high chromium steels by air and water have shown that the rusting of such steels was always local—a surface film of rust was not observed in any instance.

Having regard to both causes of the corrosion of steels, it is clear that a non-corrodible steel is not a mere figment of the imagination, and practical knowledge of the properties of 12-15 per cent. chromium steels and irons indicates the material has already arrived.

3 *The Colloidal Theory*

There remains to be noticed the recent colloidal theory of Dr. Friend. This theory claims that ferrous hydroxide in a colloidal form appears at an early stage in the course of corrosion ; this is oxidised to ferric hydroxide, still in a colloidal

form, as oxygen from the air gains access. And this colloidal ferric hydroxide catalytically accelerates the corrosion of further iron, undergoing alternate reduction by new metal and re-oxidation by fresh oxygen. In other words, the colloidal ferric hydroxide acts as a catalytic carrier of oxygen from air to metal, a type of catalytic action which is perhaps better understood of chemists than any other.

It would appear that this theory would serve to supplement rather than supplant the electro-chemical theory. The iron is brought into an attackable condition by electro-chemical forces, and the course it then follows to its ultimate destination, more or less hydrated ferric oxide, may very well be via the colloidal processes of Dr. Friend.

The above only indicates rather sketchily the manner in which the addition of a high percentage of chromium to ferrous metals has gone far to make an end of the corrosion trouble root and branch, but also furnishes the clue to the precautions to be taken with ordinary steels to fight corrosion. Firstly, see that the material is free from black scale. This is best accomplished by electrolytic cleansing. Before painting see that the steel is dry and chemically clean as possible.

Whatever flux is used for soldering in the shops chlorides will be found on all soldered fittings and many unsoldered ones (resin is not a practical flux) and the parts must be properly cleaned, the wash waters being controlled by analysis. If this is carried out effectively and a suitable paint used there is little fear of corrosion where the protecting coating remains undamaged.

It is not only in the protection of steels against corrosion that advances are being made. Recent experiments have shown that the successful treatment of light alloys is practically an accomplished fact.

Reliability

Apart from this question of corrosion it is necessary to consider in what other respects an all metal aeroplane might be structurally unreliable. I think the following will cover the ground:—

(*a*) Material not up to specifications, due either to faulty inspection or the failure of the inspection to reveal the quality of the bulk under examination.
(*b*) Subsequent mistreatment either by heat treatment or cold work.
(*c*) Undetected errors of workmanship.
(*d*) Damage to members in assembly, delivery or service.
(*e*) Failure of riveting under service conditions.
(*f*) Failure under alternating stress, *i.e.*, "fatigue."

So far as (*a*) is concerned I think that there can hardly be any doubt that metal, particularly wrought metal, is at a great advantage compared with timber. The test samples represent materials of the same composition which have gone through the same processes in the mill and the same heat treatment. The production of carbon steel bars has reached such a high standard that this material *as used* is taken as the standard reliability material by the Load Factor Sub-Committee in the section of its report dealing with reliability. In the thin strip ingot, faults, such as segregation, slag inclusion, etc., are generally noticeable and are in any case revealed in rolling or drawing together with most other material faults should they escape detection before testing. Timber is, however, only representative to the extent indicated by the theory of probability; while its inspection depends on deductions from experience concerning which there is not complete agreement among timber experts.

(*b*) Can be prevented by proper works organisation and is practically confined to those metal parts common to both metal and composite aeroplanes.

(*c*) Are far more difficult to conceal than in wood, particularly as riveting replaces welding. Contrary to popular opinion, defective riveting in properly designed members has very little influence on their strength, within the extreme limits of error experience has shown as likely to occur.

(*d*) Is also not the weak point one might imagine from the thin materials used. The very qualities which enable the members to develop a high stress render them fairly immune from the effects of rough handling, but this point has to be considered in design. That glaring damage is not fatal to the structure has been shown by reloading members broken in test. The most serious danger is fatigue failure from the repeated application of a blow on a particular point; when, for example, a portion of the shell is repeatedly bumped, say, on the tail-board of a lorry, an alternating stress failure in the form of a crack may appear; it is however very obvious and easily repaired, while with similar bad packing a wood member might be irreparably injured.

So far as (*e*) is concerned, I have already mentioned that a certain amount of rivet failure does not seriously deteriorate the structure, and there is with steel at least no evidence of the failure of riveting nor any logical reason why it should fail. In properly designed members the rivets are merely shearing pins expanded to fill the rivet holes while the heads prevent any possibility of falling out. The very remote possibility of an alternating shear stress, sufficient to cause a fatigue failure, can be guarded against in design. The rivets are in fact in much the same category as most of the bolts on an aeroplane with the difference that in the case of the rivets individual failure is of negligible importance.

On a larger scale there is extensive experience of riveting in all branches of engineering and everything in this experience tends to show that riveting is a satisfactory joining process.

(*f*) Considerable strides have been made in the last few years in understanding alternating stress failures, particularly by a better comprehension of stress distribution. Under the auspices of the A.R.C. several notable papers on this subject have been published, a study of which would remove a great deal of misapprehension. An alternating stress failure may occur after a large number of cycles in which the stress has fluctuated over a range in excess of certain values which appear to be associated with the ultimate tensile rather than the elastic properties of the material. That stress fluctuations will take place in prime movers, vehicles and similar machines is obvious from a study of their mechanism, but in a structure such as an aeroplane they are mostly due to fluctuating loads from the engine direct, varying loads on aerofoil surfaces due to the irregular wake velocity of the slipstream or resonant vibrations originating from either of these. The streamline wire is a notable exception since it has an unstable yawing derivative Nr from which the well-known sound-producing oscillation of these wires is derived.

The only direct fluctuating loads from the motor which I have known to produce failure by fatigue are the rotating couples from fixed radial engines, where these have not been allowed for in design. The maximum amplitude of resonant vibrations is generally small and the mean stress fluctuation is small, too; but the difficulty arises in the complex distribution of stress during small deformations in other than simple members. Reference to the work of Taylor, Griffiths, Coker and others, will show how complex this is and what a marked influence small but sharp changes of section have on it. Generally speaking, the avoidance of rapid changes of section (*e.g.*, sharp corners) in conjunction with material of adequate ductility, is sufficient insurance against high localised stress; metal construction falls in easily with this requirement. We can hardly go further into the subject, but it is safe to say that fatigue failures, if they occur, must be traced to the drawing office, not to the use of steel as a structural material.

Metal Covering

The desirability or otherwise of metallic covering seems to me to be largely a matter of policy. I see in the JOURNAL that Mr. O. Short puts the weight of metal covering at 0.2lbs. per sq. ft. presumably of covering. If this is the case metallic covering means an addition of 5 to 6 per cent. to the gross weight of the aeroplane—an addition which I should imagine could only be tolerated in very exceptional cases. I do not believe that it is imperative that aircraft should be *all metal*, quite a few parts—not structural—are probably better of wood except under special climatical conditions. Fabric covering, especially when it can be re-doped, really gives long service and re-covering encourages general overhaul.

Conclusion

I believe that anyone who examines the possibilities of metal construction on the lines I have indicated will appreciate the possibilities of reducing the structure weight of aeroplanes by the use of metal construction, and where they are able to supplement their deductions by experience they will be convinced of the great future in front of it. The fact that metal aeroplanes will stand adverse climatical conditions, long storage and, I believe, the wear and tear of every-day use in temperate climates better than aeroplanes largely built of timber and joined with glue is further argument in its favour.

The development of technique will undoubtedly tend more and more to eliminate the necessity for skilled labour in course of construction, and this opinion is fortified by experience. It is probable also that load factors will be able to be lowered without increasing the risk of structural failure or alternatively increase of reliability may be obtained.

I have said nothing so far on the subject of fire risks, though some improvement may be attained in this direction. Those fires in the air, resulting in a large quantity of petrol burning in a comparatively confined space, would hardly be affected if the aeroplane were made of asbestos; but since fires after a crash, probably now more to be feared, are often caused by splinters of wood coming into contact with hot exhaust pipes, this latter class of fire risk should certainly be minimised.

On looking through these notes I cannot feel that I have presented the case for metal construction as completely and convincingly as it deserves to be presented. I have been so closely occupied during the last few years with the thousand and one details of this new development that I have found it somewhat difficult to put this subject before the Society in a general way. If I had once started entering into details I should hardly know where to stop, and details as they arise will be more interesting to those who are taking up this work for themselves.

In conclusion, I should like to thank those gentlemen who have assisted me in the preparation of this paper, particularly Dr. Leslie Aitchison, who has rendered invaluable help on metallurgical matters and who kindly supplied the curves illustrating the variations of " E "; also Mr. A. E. Odgers, M.A., for the resumé on corrosion, and several other members of my experimental staff. I have also to thank Messrs. Boulton and Paul, Ltd., for permitting me, for the purpose of this paper, to make use of information and experience gained in their aeronautical department.

Discussion

The Chairman said that before throwing this extremely interesting lecture open to discussion there were two letters which he would read. One was from Mr. O. Short and the other from Major Green.

October 18th, 1922.

Chairman of Mr. North's Lecture on October 19th,
Royal United Service Institution,
Whitehall, London.

Dear Sir,

I much regret that I am prevented from attending the lecture to-night. I am in agreement with practically the whole of Mr. North's admirable paper, and I feel with the same confidence that he does that aeroplanes of metal construction will eventually show substantial advantages as against the present construction.

I should like to emphasise the need of building up the technique of design and construction, as I feel sure that once the general principles are known it is only by the continual development and improvement of detail design that metal construction can achieve the results that we anticipate. This development work calls for great patience, considerable engineering knowledge and adequate resources. It is chiefly by our difficulties that we learn, and unless we have the courage of our convictions that we are doing work which will ultimately advance aviation, we are unlikely to devote the time and energy necessary to bring the work to success.

Yours faithfully,

Fred. M. Green.

October 18th, 1922.

To the Chairman, Royal Aeronautical Society,
7, Albemarle Street, W.1.

Dear Sir,

It is a matter of regret to me that I shall not be able to attend Mr. North's lecture on "The Case for Metal Construction" as I am deeply interested in the subject.

I have, however, read the advance copy of the lecture, and I should like to congratulate the lecturer on the very able and scientific manner in which he has dealt with the subject.

I should like to point out that there is a typographical error in the advance copy of the lecture, in which I am quoted as having said that the increased weight of metal covering as against fabric covering is 2 lbs. per sq. ft.; this should be two-tenths of a pound per sq. ft. of lifting surface, or plane area, as the term is used.

With regard to this increased weight, however, it should be borne in mind that it occurs only when fabric is simply replaced by metal in the usual wing structure formed of spars, ribs and struts, and in which these members bear the main portion of the flying stresses. In future developments it will, perhaps, be possible to utilise the metal plane covering to bear the whole of the flying stresses, and from experiments carried out by my firm we are led to the conclusion that such planes, whilst giving all the advantages of the rigid metal surface, will at the same time be lighter than a steel girder structure covered with fabric.

XUM

It is evident that we are at present only touching the fringe of very important developments in the metal construction of aircraft, and I submit that it behoves those who seek the most rapid advance in aircraft design to keep an open mind on the subject and not to allow purely theoretical considerations to confine this development in one direction or another.

In this connection I particularly refer to the choice of metals without taking sides for or against the use of steel or aluminium alloys. I have used these materials in conjunction and when they appear to fit in best with our requirements, and the numerous experiments which my firm has carried out during the last three years strengthen my conviction that such a combination may be used with the utmost safety and reliability.

Quite recently we carried out a destruction test on the tail plane of a machine which was constructed with tubular steel spars and duralumin ribs, and has been in use over two and a half years. It withstood a loading of 40 lbs. per sq. ft. for 65 hours, and was then loaded to 60 lbs. per sq. ft., at which figure it failed. On opening up the plane for inspection purposes we discovered that the methods we had adopted for the prevention of corrosion and rusting were so effective that not the slightest signs of either of these disabilities were visible. This tail plane may be seen by anyone who is sufficiently interested in the subject to visit our works at Rochester.

Yours sincerely,

OSWALD SHORT.

Air Ministry, Kingsway, W.C.2,
October 24th, 1922.

Dear Sir,

I was unfortunately prevented by work at the Air Ministry from attending Mr. North's very interesting lecture on metal construction.

I have always been a great supporter of metal construction in aircraft, and I was delighted to see the conclusion at which Mr. North had arrived. If his claims are valid, as I believe them to be, the introduction of metal construction will be the biggest step in progress towards making air transport self-supporting which has been achieved since the end of the war. I only hope that designers, in spite of their present financial difficulties, will push on towards effecting designs in metal with all possible energy.

Yours very truly,

W. M. BRANCKER.

The Secretary, Royal Aeronautical Society,
7, Albemarle Street, W.1.

I am pleased to hear from General Brancker that he is in favour of making every effort to utilise the commercial advantages to be obtained by the incorporation of steel with its lighter structure into aeroplane design.

Unless, however, some direct assistance is available I am afraid it will be some time before these conditions will be available to users of commercial aircraft.

Continuing, the CHAIRMAN said he noticed among the audience several people who were specially entitled to speak on this subject, and he would ask them to keep their remarks within a definite time limit. He did not wish to fix the limit too rigidly at the moment, but he hoped those who spoke would bear the point in mind.

Major WYLIE said he considered Mr. North had presented a very big subject in a very comprehensive and able manner. He agreed with almost everything that had been said, and with some things he agreed enthusiastically. For instance,

Mr. North had said that the best way to master the art of forming strip to make spars was to live and learn, and he agreed with that enthusiastically. Mr. North indicated that the behaviour of the strip in springing back from the dies was governed by the elasticity of the strip, *i.e.*, by the elastic limit or the proof stress. He himself, however, had found that the ultimate strength was the deciding factor, because in bending the strip was bent to such a curvature that it was stressed very much beyond the elastic limit and even beyond the yield. He would like Mr. North's opinion on that point. The next point that he agreed enthusiastically with was that in order to design a steel spar properly, skill and judgment must be used. He thought Mr. North's illustration of the prowess of the billiards player was very illuminating, particularly in one respect, viz., that the success of the billiards player could be judged immediately by whether the ball went into the pocket or not. He would like to know how Mr. North judged the success of the designer; whether it was by applying some formula by which the strength of the design could be calculated or whether it was only by a method of testing. If it was by a formula, he would like more information as to what formula was applied and how it was applied. There was one point upon which he did not agree with Mr. North. It was stated in the lecture that it has been customary for some time to identify the proof stress with the maximum stress realisable in thin-walled structures, however small the curvature might be with respect to the thickness of the shell. He did not know whose custom this had been, but it certainly had not been his (the speaker's) custom. About seven years ago he had used it to test a great many tubes in compression, and he found that tubes with a ratio of radius to thickness of 40 to 1 would fail completely and crush up when the stress was about equal to the yield stress, whereas tubes that were much thicker than this and with the same diameter would stand up to a stress which was in excess of the ultimate strength of the material, and when very thin tubes were tested the stress developed might not reach even the yield point strength of the material. When he came to the very much thinner members that were used for spars, he found that, if these were of high tensile steel, he never got up to the yield point of the material. He got a number of spars which were very similar and which appeared to be of fairly stable section, as they would take a set before they failed, *i.e.*, they would not fail when the material was stressed to the elastic limit, but neither did they stand up to a stress equal to the ultimate strength of the material. He found that they usually failed when the permanent set in the strip at the point of failure was equal to about 0.1 per cent., and the proof stress had been defined, as stated by Mr. North, in order that it might be a criterion for the strength of the spar in which it was used. He believed that if members were designed so that the elastic stability of them was sufficient, it would be found that the member would fail at approximately the proof stress as determined in a tensile test. It had been his practice to design spars so that if he expected them to stand a stress of 70 tons per square inch, with material having a proof stress of 70 tons, the critical stress, *i.e.*, the compressive stress at which the member would fail if the material were elastic, as high as the critical stress, and if the section were ideally perfect, would be in the vicinity of 120 tons to the square inch. The other day he had to test an interesting section in the form of a large corrugated tube which was made of steel specified to have a proof stress of 40 tons per sq. in. He calculated that if the section were absolutely true, and if the material were elastic up to 77 tons per square inch, the critical elastic stress would be about 77 tons per square inch. The member failed at a stress of 46 tons, and the proof stress, as determined by Dr. Aitchison, was 45 tons. Such close correspondence between failing stress and proof stress was got fairly regularly, and therefore he felt that the proof stress, as at present defined, was not so unsatisfactory as Mr. North made it appear. At the same time, he agreed that the tangent to the stress-strain curve was an important factor.

Mr. W. D. Douglas said that he also agreed with Mr. North in most of

what he said. With regard to riveted joints, he had had the opportunity of testing a fair number of samples of metal construction which utilised rivets for jointing purposes, and there had been very few cases in which the riveting had been defective. He was referring to small defects in riveting and not those which were very easily observable. That confirmed Mr. North's statement that commercially defective riveting was not frightfully important. Of course, it all depended on the nature of the member. In certain cases, every rivet counted, but in the majority of cases one rivet would not affect the strength of the structure seriously. Also, in subjecting these structures to vibration tests, he had had extremely few cases of failure of the rivets in the steel members. Where they had failed they had generally been extremely defective in workmanship. He was referring here to such defects as should not pass any reasonably efficient inspector. Much more information was needed in connection with the design of riveted joints for aircraft. The case of bridge construction was not entirely parallel because some alternating stresses were obtained in metal aircraft that were not usually present in bridge construction, and it might be that the design of riveted joints to withstand alternating stresses should be founded on quite a different basis to that which controlled the design of joints for static loads. For instance, in joints designed for static loads it was generally assumed that if the drilling and riveting had not been done with micrometrical accuracy, the ultimate "give" in the material would distribute the load among the various rivets and make each of them do its fair share. Also, according to the work of Prof. Batho, the friction in the joint played a very important part in determining its strength. In vibration, or under alternating stress, it was not safe to count on the ductility of the material distributing the load. There was a parallel case in the effect of alternating stress on other ductile materials. Ductile materials in general, under alternating stress, behaved apparently as if they were extremely hard and brittle and without any ductility. For instance, a piece of new plasticene, which was almost infinitely ductile—its reduction of area was 100 per cent. in tension—if subjected to alternating stress, behaved like a piece of sulphur. If there was a small scratch on the surface there developed a crack extending from the scratch and there was a granular appearance in the fracture. It was not safe, therefore, in riveted joints to depend upon ductility for making up small errors in manufacture. Also, it was uncertain what the frictional effect of the riveted joint would be in alternating stress, although so far there had been practically no trouble with steel construction. He could not, however, at the present moment say the same about aluminium alloys. He had had a case of failure of riveted joints in an aluminium alloy spar. It was a single sample of joint, and it had failed twice in vibration, and a similar joint which had been in flight had shown traces of movement when it had been subsequently opened up. The fact that a joint had been moving in the air did not inspire confidence, but he did not wish to put this forward as detracting from the use of aluminium alloys, but merely as an instance, showing that more information as to the design of such joints was required.

Dr. A. P. THURSTON thought that everyone present would join in congratulating their old friend Major Wylie on the complete recovery from a most serious illness.

He congratulated Mr. North most heartily on an interesting paper, and like Major Wylie, he agreed enthusiastically with Mr. North in everything he had said, but regretted being unable to discuss the paper as fully as it undoubtedly deserved owing to the fact that he had not read the paper before the lecture.

One of the principal objects of present experiments in metal construction was to obtain data to enable the strength of metal aeroplanes to be calculated with accuracy. Another object was to obtain the shapes of the sections which gave the best results in practice. It was not easy to place the various sections

in order of merit without careful analysis, so much in fact depended upon the means of comparing experimental results that he would be interested to know what formula or formulæ Mr. North used for comparing the efficiency of the various sections which had been evolved.

Metal construction, in his opinion, was still in the experimental stage, and solid progress would apparently be most easily achieved by a system of experiments devoted exclusively to obtaining the data or the coefficients required in the various calculations. He would be interested to know whether Mr. North had obtained curves

(1) For failing loads on flanges of various thicknesses and curvatures, and
(2) Of the relation between the curvature of the roll and the finished curvature of the strip.

He felt that the problem of metal construction had suffered from a tendency to make all-metal construction a fetish, that is to say, there appeared to be a tendency to construct every part of the machine of metal whether metal is the most suitable material or not, in order to be able to say that the construction was all-metal. He thought that in the present state of the science a composite construction was the most suitable one, at least for small machines.

In this connection it should be remembered that the great driving force behind metal construction during the last few months of the war was the shortage of suitable seasoned wood. If by any unhappy calamity we should again be involved in war, the same problem would confront us, but magnified a hundred times. It appeared, therefore, a sound and essential policy for the authorities to concentrate their experiments on the vital members of aircraft, *i.e.*, on those parts which used a lot of wood and carried main loads. When these experiments were finished, then, the problem of the minor parts could be solved. This was the way he had endeavoured to tackle the problem during the last six months of the war. The experiments were chiefly concerned with

(1) Obtaining suitable sections for the vital members.
(2) Determining the best materials for particular purposes, and
(3) The scientific properties of the materials and the sections to enable calculations to be accurately carried out.

In this latter connection it was necessary, for instance, to discover and define the scientific properties of steel which caused local collapse due to local bending. Was this local collapse dependent on a limit of proportionality, the yield point, or upon some other property? After much experiment it appeared that neither the yield point nor the limit of proportionality could be taken as giving a just measure of the strength of thin steel sections. A limit of proportionality, *i.e.*, an elastic limit, of 15 tons per square inch and a yield point of 90 tons per square inch were not uncommon in the early experiments. It was not until the discovery that the ultimate strength of a section did not strictly depend upon either of these properties, but upon some intermediate property, that suitable materials were evolved for metal construction.

It was found from experiments that the strength of a section depended upon an arbitrary figure which has been defined as the "proof stress" or "effective strength" of the material. The "effective strength" is defined as stress which causes a permanent set of one-thousandth of the length of the material. Doubtless a more accurate definition will be evolved as experiments proceed, but this arbitrary definition appears to fit in best with the experiments already conducted.

The stability of a section does not depend upon its scale provided that all the dimensions are maintained in the same proportion. It follows, therefore, that the calculation of the strength of various spars or the like is a simple matter if ample experimental data is available. He would, therefore, advocate an organised series of experiments in connection particularly with the vital members,

as this would provide the nation with a fund of information which would be immediately available should necessity arise. In any case, this information would be of more immediate practical value than a series of curves giving only some theoretical aspect of the subject.

In conclusion, he wished to convey his personal thanks to Mr. North for once again bringing this important subject forward, and congratulated him on his interesting and valuable paper.

Mr. NORTH, replying to the discussion, said he would first deal with one or two points made by Dr. Aitchison in which he did not agree with the paper as regards corrosion. In the section dealing with the electro-chemical theory, the paper said "(4) The physical condition of the material, due to heat-treatment or mechanical working. Strained or unstrained portions of a homogeneous material constitute an active voltaic couple. There is nothing here that proper care in the selection, manufacture and handling of the material cannot successfully deal with." He was afraid that the last part of this statement was too far-fetched. It was quite true that although it was a theoretical possibility, it was not something which we could actually hope to obtain. The other point mentioned by Dr. Aitchison was that it was suggested in the paper that the portion dealing with corrosion led up to the reason of the non-corrosive properties of the 14 per cent. chromium steel, but he was afraid there was a big gap and it was rather hopeless to try and bridge it within the scope of the paper. Therefore it was not quite true to say that it indicated the reason for the immunity of that class of steel from corrosion.

With regard to Mr. Short's letter, the figure of 2 lbs. instead of 0.2 lbs. was a typographical error, but it did not affect the argument because he did not use the 2 lbs. in measuring the percentage. Mr. Short now said that he meant the plane area and not the covering surface, so that the increase of weight would be something of the order of 3 per cent. Mr. Short had said that he hoped to be able to produce aluminium covered wings lighter than steel, and he himself could only reply by saying that he hoped by that time he would have produced wings which were lighter than aluminium ones.

He would very much like to emphasise what Major Green said in his letter as to people having the confidence of their convictions. Mr. Handley Page had once accused him (Mr. North) of being a fanatic. Indeed, Mr. Handley Page had said that he was a fanatic on all-metal construction and that he (Mr. Handley Page) was a fanatic on the subject of slotted wings. He did not mind being called a fanatic, however, because he did not think it was possible to get over the disheartening early stages of any work of this sort unless they made up their minds that they had confidence in their convictions, and it was his convictions which he had tried to outline in the paper. His convictions were the reason why he had confidence, and he believed that there were many other people who had had experience of all-metal construction who had the same confidence that he had.

Major Wylie had referred to the springing back from the rolls. The paper had suggested that this was due to the resilience of the material, and he had thought it was a very good method of abbreviation to use the term resilience; but Major Wylie had found him out in this. What actually governed the spring back, he presumed, was the potential strain energy of the strip as it came out of the roll. Some parts had been plastically deformed, and others elastically stretched, and the amount of spring back would depend on the strain energy of the strip as formed. He certainly did not mean to suggest that it was associated in any way with the elastic limit or the yield point or the ultimate. He simply suggested that it was, in an extremely complicated way, associated with the shape of the stress-strain diagram, not the limit of proportionality, a statement to which he thought Major Wylie would not take exception. He believed that Major Wylie associated it with the ultimate strength of the

material, and he also believed that Major Wylie's method of dealing with these calculations gave reasonably accurate results. At the same time, he did not know on what solid grounds the method of calculation rests. Both Major Wylie and Dr. Thurston asked what was the formula for testing the designer. It was a very simple test; it was the structure weight of the aeroplane which the designer built. The whole object of aircraft structural design was to make a reliable structure of a certain strength and get it as light as possible, and he could not think of any test or formula which would enable the designer to be put to the test. In fact, he thought it was purely a matter of engineering judgment. If these things could be assessed in terms of formulæ, all that would be necessary would be to have a book and the office boy could take the book out and design. But the individual circumstances had to be taken into account in every case, not only in regard to aeroplanes but in regard to all engineering design.

Major WYLIE said his question was what formula was used to test the actual strength of the section when it was designed.

Mr. NORTH said the strength of the section was defined in terms of the compression loads and the external shear loads.

Major WYLIE said that perhaps he might explain himself better. The Paper gave two formulæ—one for a perfect tube and the other for a flat rectangular plate loaded uniformly in its plane and supported at its edges. What he wanted to know was whether Mr. North had a formula which could be applied to the structure he designed.

Mr. NORTH: You are referring to a formula for knowing the elastic instability.

Major WYLIE: Yes.

Mr. NORTH said he did not suggest that he could put forward a formula based on any rational grounds at all. He only gave the formulæ in the paper because they showed what the variables are, but it was a comparatively easy matter to satisfy oneself whether a spar would stand up to a certain load or not. It really came back to the billiards table point all over again. Major Wylie, in the matter of metal construction, was a very expert performer. There was one fact in this connection, however, to which he (Mr. North) had not made any reference in the paper because he felt he had received the information in confidence, but he believed that Major Wylie had developed a method of calculating the stress at which instability would occur and one which, he believed, gave very satisfactory results. Though he was familiar with Major Wylie's formulæ, he was not aware, however, of the grounds on which they were founded, *i.e.*, how Major Wylie bridged the gap between the simple cases and the complicated cases which occurred in practice. Major Wylie had also spoken of the yield point of high tensile steel. The yield point of high tensile steel was a very vague term and it did not satisfy the proper definition of yield point. He did not mean in the paper, when he said it was customary to assume that the proof stress was the maximum realisable, that it was the maximum realisable in any material. He meant it was identified with what one could expect to get by the best design, using that particular material. He thought the discrepancy between Major Wylie and himself was due to the fact that he had not made himself clear.

Major WYLIE said he thought that probably was so.

Mr. NORTH, continuing his reply, said he was pleased that Mr. Douglas had said that his experience with riveting agreed with what was said in the paper, although he very properly pointed out that there were circumstances in which the riveted joints of metal aeroplanes are stressed with types of alternating stresses which were somewhat outside general engineering experience, but as Mr. Douglas had said, as far as was known at present, there was no special trouble arising

with the types of connections now used. To what extent it would be possible to simplify these joints as we gained more experience remained to be seen. Dr. Thurston had suggested that he had not put enough of his wares in the window. He did not know whether that was a reasonable thing to expect even if he had all the information that Dr. Thurston wanted, and he had not. The fact was that these things did not belong to himself, but to the firm for whom he worked and he did not know that it was a reasonable thing to ask them to allow him to publish a wholesale accumulation of data. If they were put in at all, they would have to be of a very voluminous nature, and he did not think that that was the proper way of looking at the subject at all. It was better to look at it from broad principles. If they were satisfied with the broad principles, then they could work on similar lines and obtain their own experimental results. He did not think a large amount of experimental data, although helpful in some respects, was necessary in presenting what he had been careful to call this paper, the case for all-metal construction, not the first guide to metal construction or how to design metal aeroplanes, or anything of that sort. The paper was merely the presentation of the reasons for what he believed to be the bright future for this class of construction. In actual practice, the difficulties which were arising in making metal aeroplanes were not the difficulties of designing satisfactory spars. That did not represent the trouble of designing. The designing of spars took about one-tenth of the work of one member of the staff. It was one of the least troublesome parts of the whole job. The difficulties were an accumulation of small details due to the young, weak and inexperienced drawing office technique, and not the difficulty of making a section which would stand up to a given load. The difficulty was to produce on paper a shape which could be reproduced in the shops and incorporated in a reasonable structure. It was in this direction that the greatest difficulties arose. If they were to attempt to standardise large numbers of types of sections, they would only be tending to restrict development of technique by leading people to believe there was some particular virtue in some particular shape. In the end, the design turned on the general *motif* or theme of the whole structural system. It was a thing which was very difficult to define. It was not a scientific matter at all, but underlying any engineering structure or mechanism there was a kind of theme or *motif* which was carried through the whole design, and by maintaining that theme it was possible for the engineer to produce what was called an engineering job.

The PRESIDENT said the lecture had been an extremely interesting one, and had taken as its main theme really the idea of live and learn. Living and learning was not restricted to engineering or to any branch of engineering, and he did not believe that anybody under-valued it when they came to think of it at all. When all was said and done, the whole object of education was living and learning in order that the younger members of the community might learn what had been the experience of their predecessors and help them to learn it quickly. It was the efforts of designers such as Mr. North, who were gaining further experience, which some day—perhaps a decade hence—would be handed down to the students of our colleges as matter which was then standardised although at the present moment, as Mr. North had indicated, it was a perpetual difficulty. This always meant expense and it needed a great deal of courage. He therefore asked those present to accord Mr. North a hearty vote of thanks for his paper.

The vote of thanks was carried with acclamation, and the meeting closed.

ESTIMATION OF WEIGHT OF AEROPLANE PARTS

BY EDWARD P. WARNER, ASSOCIATE FELLOW.

The aeroplane designer, in making up a weight schedule and calculating the centre of gravity of a projected machine, usually relies entirely upon his past experience and upon those data concerning the products of other designers which he may have been able to accumulate in his files, and it is seldom that the weight estimates and balance computations are checked, after the completion of the detail design and before the construction of the aeroplane, by carefully calculating, from its volume and the specific gravity of the material of which it is made, the weight of each separate element entering into the construction. Unfortunately, it is not often that any thorough weight analysis is carried through even after the construction is completed, or that each part going into the structure is weighed during the progress of the assembly, and the weight data available for the use of the designer are therefore much less complete than they might and should be.

Although the general practice is to depend on past experience and knowledge of the weights of similar parts in aeroplanes of types similar to that under consideration, there are times when it is very desirable to have a general formula for the weight of a part, either in order to furnish a basis for estimating with increased accuracy the weights on a new machine of a type or size differing somewhat from any in the designer's experience, or more frequently to make possible an estimate of the effect on the weight of some change in the form or dimensions of an aeroplane.

It is obvious that no such formulæ can apply accurately to all cases. The methods of construction differ so widely that it is perfectly conceivable, for example, that two aeroplanes may be exactly similar in external form and appearance and have the same total weight when loaded, yet have wing structure weights differing from each other by as much as 40 per cent. Although it is impossible for any of them to be of universal application, general formulæ may nevertheless be very useful if they are correctly derived and if they are applied with due regard for their limitations.

The fundamentals which govern the derivation of rational weight formulæ were first discussed by Normand with reference to ships, and have recently been applied by Commander J. C. Hunsaker to the detail weights of rigid airships. The same principles are equally applicable to the case of the aeroplane, but have seldom been used in that connection. There are many formulæ for the weight of aeroplane parts, but most of them are purely empirical and there is wide disagreement among them, not only as to the numerical coefficients to be used, but also as to the form assumed by the expression for the weight of any particular element and as to the exponents to be attached to the several factors.

In forming these weight equations it is necessary to treat each class of member separately, later combining the formulæ thus obtained to secure a single expression for the weight of a whole assembly such as the wing truss. In the course of this article the major assemblies which make up the aeroplane structure will be discussed in turn, and each assembly will be dissected and an analysis made of the laws which govern the weights of the components.

Wing Weights.

The most important single element of the wings in respect of weight is the spars. The spars are stressed in bending and also in compression or tension, and the variation of weight must therefore be examined from three separate standpoints.

The bending moment in a beam with any given type of loading is proportional to the product of the total load carried and the length of the beam. Since the length of a wing spar is proportional to the span of the aeroplane, the bending moment is proportional to the product of the total weight and the span. In order that the stress in the extreme fibre may be a constant, the section modulus must vary in the same ratio as the bending moment. If it be assumed that the flange thickness is a fixed fraction of the total depth of the spar, that the width can be changed independently of the depth, and that the ratio of web thickness to width of flange remains constant, the section modulus will be proportional to the width of the flange and to the square of the depth. The depth of the spar varies as the thickness of the wing, and this, if the same aerofoil section is used throughout, is proportional to the chord. The results so far obtained may then be summarised in symbolic form: —

$$M \text{ varies as } WS \qquad WS \text{ varies as } bd^2 \text{ varies as } bC^2$$

where M = max. bending moment. b = width of spar flange.
W = total weight of aeroplane. d = spar depth.
S = span.
C = chord.

The weight of the spar is proportional to the product of its maximum length, breadth and depth, or to the product of span, chord and flange width. Since, by transforming the proportionality just written,

$$bC \text{ varies as } WS/C$$

it follows that

$$W_s \text{ varies as } WS^2/C$$

where w_s is the spar weight. This may be written in the alternative form

$$W_s \text{ varies as } WSR$$

letting R represent the aspect ratio. The wing spar weight, in so far as bending stresses are concerned, is therefore proportional to aspect ratio, to total weight and to span. If the aspect ratio is varied while the area is kept constant, and neglecting the small variation in total weight, the weight varies as the three-halves power of the aspect ratio, for the span is proportional to the square root of the aspect ratio for a given area.

If the spar fails by buckling, the moment of inertia of the cross section must bear, to insure safety, a fixed proportion to the product of the square of the length and the end load. The end load is proportional to the product of the total weight and the ratio of span to gap, while the length of a bay varies as the span and the moment of inertia of the section as the product of the width of spar flange and the cube of the spar depth, or the cube of the chord. Written in symbols, assuming the gap-chord ratio constant,

$$bd^3 \text{ varies as } bC^3 \text{ varies as } WS^2\,(S/C)$$

The spar weight, as before, is proportional to the product of span, chord and width of flange, or

$$W_s \text{ varies as } bCS \text{ varies as } WS^4/C^3 \text{ varies as } WSR^3.$$

This expression is of the same general type as the other, but the aspect ratio now enters in in the third power. It will be noted in both cases that the ratio of spar weight to total weight varies as a linear dimension, and it will be found that this is true of weight formulæ in general.

If the bays are supposed to be short enough so that the spar would ultimately fail under the compressive load by straight crushing instead of by buckling, this being the common assumption in calculating stresses, the cross sectional area must be proportional to the end load and the expression for spar weight is identical with that derived in the case of bending. In general, therefore, the formula

$$W_s = KWSR$$

may be taken as representing the weight of wing spars subjected to combined stress.

An exactly similar analysis may be made for rib weights. Ribs are subject to bending stress only, and the section modulus must therefore vary directly as the product of the load, which is proportional to the product of the load per sq. ft.

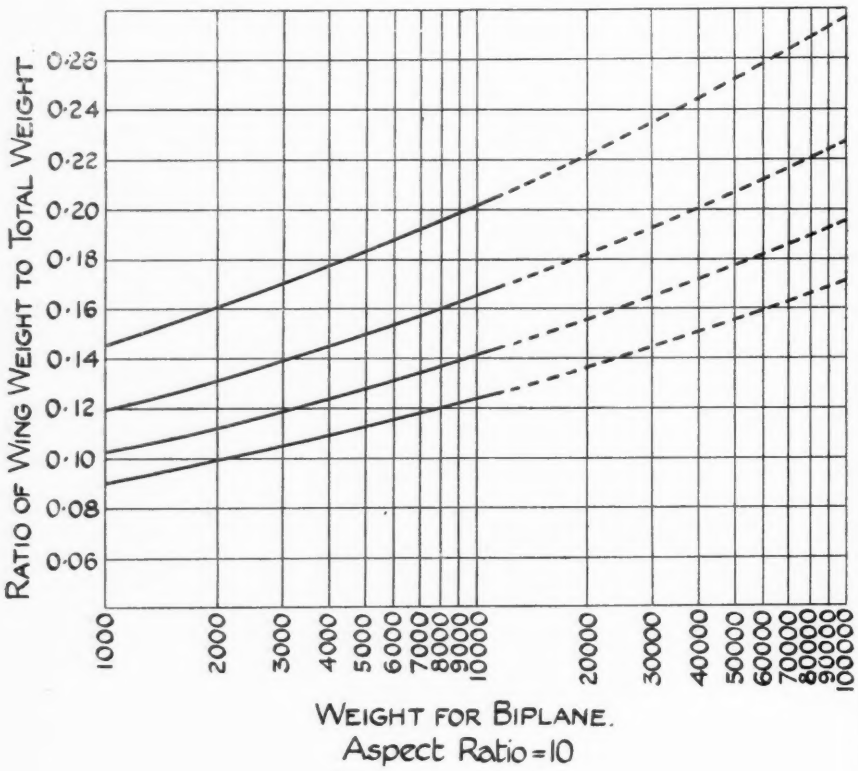


FIG. 1.

on the wing, the chord and the rib spacing, and the length of rib. The last-mentioned quantity may be represented by s. In symbolic form,

$$bd^2 \text{ varies as } bC^2 \text{ varies as } (W/SC)\,CsC \text{ varies as } WC\,(s/S)$$

and

$$w_r \text{ varies as } bC^2 \text{ varies as } WC\,(s/S)$$

$$n \text{ varies as } S/s$$

$$nw_r \text{ varies as } WC$$

where w_r is the weight of a single rib and n the number of ribs; b and d in the above equations, of course, relate to the dimensions of the rib, not of the spar. The total rib weight should therefore be independent of spacing, were the material utilised with equal efficacy in all ribs and, unlike the spar weight, it goes down as the aspect ratio goes up.

The weights of the interplane struts and of the drag struts within the wing follow the same laws. In both cases the geometrical form of the cross section

may be considered as fixed, both dimensions varying together, whereas in the spar one dimension is fixed and the other must vary alone. Since these struts are long columns failing by buckling, and since the compression in any strut is proportional to the shear in the wing truss at that point or to the total weight carried,

$$d^4/l^2 \text{ varies as } W$$

$$w_t \text{ varies as } d^2l \text{ varies as } \sqrt{d^4l^2} \text{ varies as } l^2\sqrt{W} \text{ varies as } C^2\sqrt{W}$$

l being the length of the strut and w_t the strut weight. In this case the ratio of

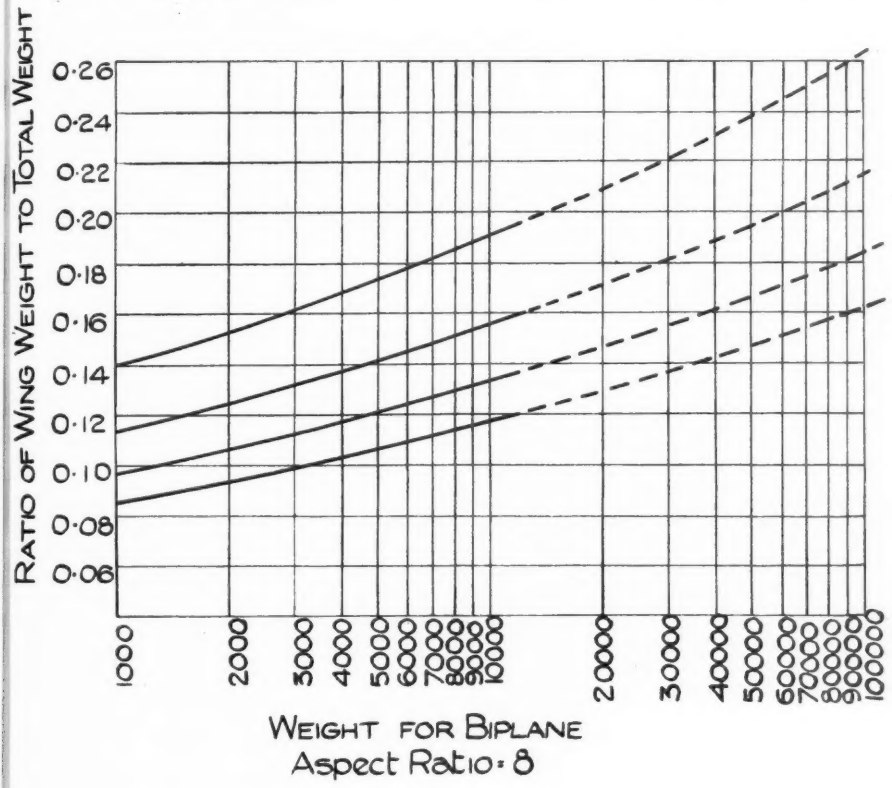


FIG. 2.

part weight to total weight cannot be taken so directly as in the others already examined, but it is clear that if the unit loading and the aspect ratio remain constant the chord must vary as the square root of the total weight. Once more, therefore, the part weight is proportional to the product of the total weight carried by a linear dimension of the structure.

The strength, and consequently the weight, of the fabric used on the wings is theoretically dependent on the rib spacing and the unit loading. In actual practice, however, the same sort of fabric is used on virtually all aeroplanes, and the weight of the fabric is therefore simply proportional to the area.

The only remaining elements of importance in the wing structure are the wires. The wires always being in tension, their sectional area must be directly

proportional to the load, and the weight varies as the product of the load and the length. If a flying wire makes the angle θ with the wing, or an internal drag wire the angle θ with the spar, the load and the wire is proportional to W cosec θ and its length to S sec θ, always assuming a constant number of bays and a constant ratio of gap to chord. The weight of the wires being equal to a constant times the product of these two quantities,

$$w_w \text{ varies as } WS \sec\theta \operatorname{cosec}\theta \text{ varies as } 2WS/\sin 2\theta$$

θ, for both lift and drag trusses, almost always lies between 30° and 45° and $\sin 2\theta$ therefore lies between .87 and 1. As an approximation never involving an

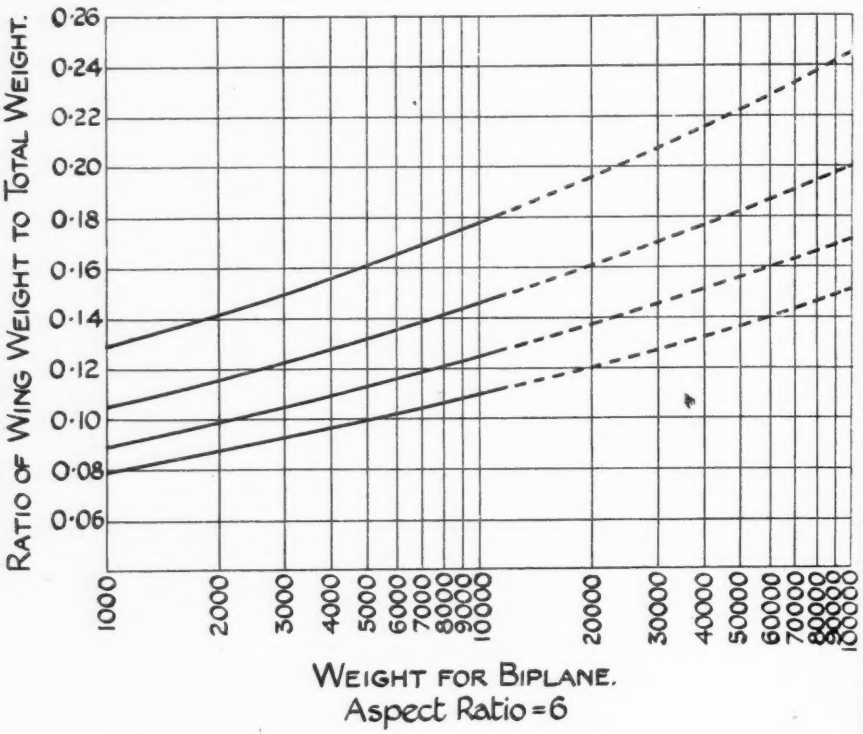


FIG. 3.

error of over 8 per cent. from the average $\sin 2\theta$ may be considered as constant and omitted from the equation of proportionality, which then becomes

$$w_w \text{ varies as } WS.$$

Since it is very seldom expedient, in making up a weight schedule, to treat separately each element such as the spars and ribs, it is desirable that all of the formulæ so far secured be combined in a single expression. This can be done, for a group of designs reasonably similar in type, by finding the average weight of each element in aeroplanes already built and then assigning to each an importance in the combined formulæ proportional to the share which it contributes to the total weight.

If W_2 and W_1 be the total weight of two assemblies of roughly similar type,

and w_{a1} and w_{a2}, w_{b1} and w_{b2}, etc., be the weights of the elements which make up the assemblies,

$$W_2/W_1 = (w_{a2}/w_{a1}) \times (w_{a1}/W_1) + (w_{b2}/w_{b1}) \times (w_{b1}/W_1) + (w_{c2}/w_{c1}) \times (w_{c1}/W_1) + \ldots$$

If, further, $w_a = KA^x B^y C^z$, as in the elementary weight formulæ just derived, A, B and C being dimensions of the structure,

$$w_{a2}/w_{a1} = (A_2/A_1)^x \times (B_2/B_1)^y \times (C_2/C_1)^z.$$

If the ratios A_2/A_1, B_2/B_1, etc., are not far distant from 1, or in other words, if no very large change is made in the dimensions, the above expression is approximately equal to :—

$$w_{a2}/w_{a1} \fallingdotseq [1 + X(A_2/A_1 - 1)] \times [1 + Y(B_2/B_1 - 1)] \times [1 + Z(C_2/C_1 - 1)]$$

and this, again neglecting the products of two or more fractions, is approximately :—

$$w_{a2}/w_{a1} \fallingdotseq 1 + X(A_2/A_1 - 1) + Y(B_2/B_1 - 1) + Z(C_2/C_1 - 1)$$

$$\text{if } w_{b2}/w_{b1} = (A_2/A_1)^P \times (B_2/B_1)^Q \times (C_2/C_1)^R$$

$$\text{and } w_{c2}/w_{c1} = (A_2/A_1)^T \times (B_2/B_1)^U \times (C_2/C_1)^V$$

$$W_2/W_1 = 1 + [(Xw_{a1} + Pw_{b1} + Tw_{c1} + \ldots)/(w_{a1} + w_{b1} + w_{c1} + \ldots)](A_2/A_1 - 1)$$
$$+ [(Yw_{a1} + Qw_{b1} + Uw_{c1} + \ldots)/(w_{a1} + w_{b1} + w_{c1} + \ldots)](B_2/B_1 - 1)$$
$$+ [(Zw_{a1} + Rw_{b1} + Vw_{c1} + \ldots)/(w_{a1} + w_{b1} + w_{c1} + \ldots)](C_2/C_1 - 1)$$

and this is approximately equal to :—

$$W_2/W_1 = [1 + \{(Xw_{a1} + Pw_{b1} + Tw_{c1} + \ldots)/W_1\}\{A_2/A_1 - 1\}]$$
$$[1 + \{(Yw_{a1} + Qw_{b1} + Uw_{c1} + \ldots)/W_1\}\{B_2/B_1 - 1\}]$$
$$[1 + \{(Zw_{a1} + Rw_{b1} + Vw_{c1} + \ldots)/W_1\}\{C_2/C_1 - 1\}]$$

and, again approximating,

$$W_2/W_1 = \{(A_2/A_1)^{Xw_{a1}/W_1 + Pw_{b1}/W_1 + Tw_{c1}/W_1 + \ldots}\}$$
$$\times \{(B_2/B_1)^{Yw_{a1}/W_1 + Qw_{b1}/W_1 + Uw_{c1}/W_1 + \ldots}\}$$
$$\times \{(C_2/C_1)^{Zw_{a1}/W_1 + Rw_{b1}/W_1 + Vw_{c1}/W_1 + \ldots}\}$$

The detail weights for a number of aeroplanes of the two-seater tractor biplane type have been examined and it has been found that the average distribution of weight among the several elements of the wing structure, neglecting minor elements which, combined, make up about 18 per cent. of the total weight, is as shown by the table below.

Element.	Per cent. of weight.
Spars	34
Ribs	16
Struts	24
Wires	10
Fabric	16

Then taking, according to the method just derived, the weighted average of the exponents with which the several factors enter into the elementary formulæ, it is found that the wing weight should vary in accordance with the formula

$$W_w = K_w W^{.72} S^{.94} C^{.46}$$

or alternatively,

$$W_w = K_w W^{.72} S^{1.40} R^{-.46} = K_w W^{.72} R^{.94} C^{1.4}$$

If the wing loading be introduced as a variable in order to eliminate all quantities directly dependent on size except the weight the equation becomes :—

$$W_w = K_w W^{.72} A^{.7} R^{.24} = K_w W^{1.42} (W/A)^{-.7} R^{.24}$$

Since the span and chord are taken for a single supporting surface the weight used in these formulæ should be that taken by a single set of wings, or

one-half the weight of a biplane, for example, when W_w becomes the weight of the single set of wings. The area denoted by A in the formula is also that for a single supporting surface. The total wing weight for a monoplane would therefore be 32 per cent. larger than for a biplane of the same total weight, total area and aspect ratio, and having the same value of K_w. The wing weight for a triplane, similarly, would be 16 per cent. less than for a similar biplane.

The value of K_w has been determined for a number of aeroplanes of service type, ranging in weight from 1,100 to over 10,000lbs., and the values found are plotted against weight in Fig. 1. It will be observed that most of the points are grouped close to a smooth curve, and where there is a large deviation from the

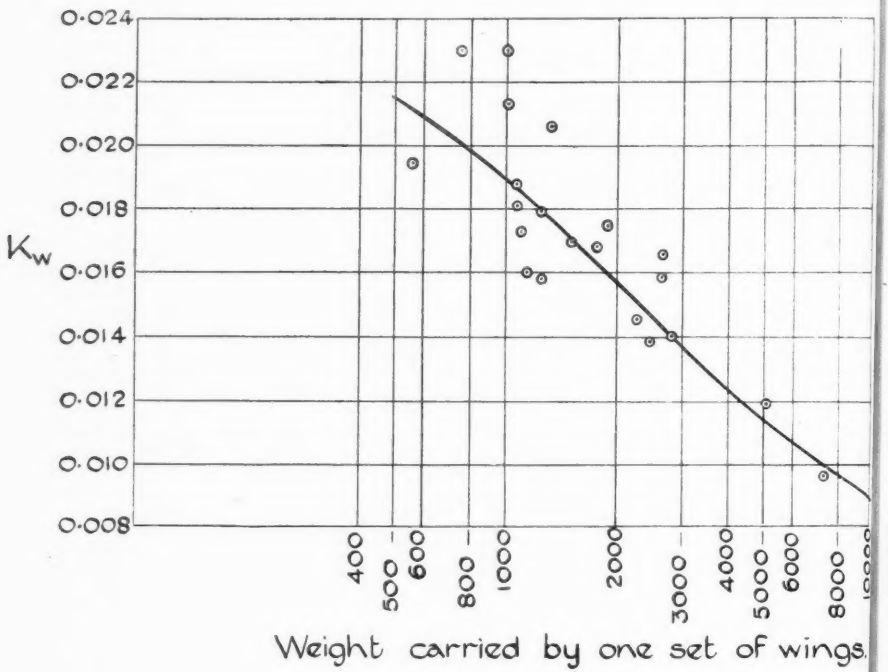


FIG. 4.

curve it can generally be accounted for by peculiarities of the design. The wing weight constant for cantilever trusses, for example, lies well above the mean curve in the cases for which data was available, while that for machines in which the interplane bracing is unusually profuse and the unsupported spar spans short lies below the curve. Aside from eccentricities in amount and arrangement of external bracing, the location of a point on the chart with respect to the mean curve gives a fair measure of the efficiency of construction of the wing cell.

The curve given for K_w can be represented with reasonable accuracy (within 5 per cent. at all points in the range shown) by the equation

$$K_w = 1/8.11\ W^{.276}$$

If this equation be combined with the original forms they become:—

$$W_w = .123\ W^{.44} S^{.94} C^{.46}$$

$$W_w = .123\ W^{1.14}\ (W/A) - .7R^{.24}$$

The second equation shows that, on the basis of present practice, the improvement in constructional efficiency with increasing size is insufficient to overcome the handicap inherent in the large structure, and the ratio of wing weight to total weight therefore tends to increase as the size of the structure grows. In Figs. 2 to 4 the ratio of wing weight to total weight is plotted against total weight for a number of wing loadings and for three different aspect ratios. These three sets of curves are drawn for biplanes. The corresponding figures for monoplanes are

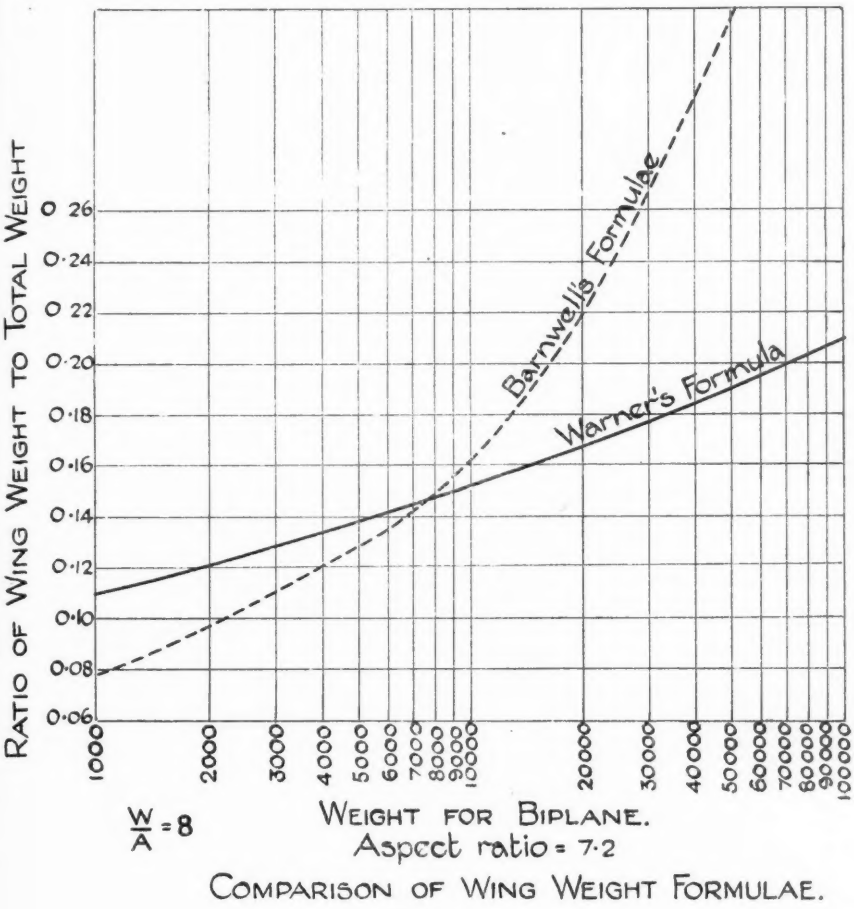


FIG. 5.

equal to those for biplanes of twice the weight, while the actual weight of a triplane must be multiplied by two thirds before seeking its wing weight ratio on the chart. The dotted portions of the curves are beyond the limits of present practice and the extrapolation is admittedly uncertain. The weight of the wings in very large aeroplanes is of course dependent largely on the degree to which the weight of the power plants and useful load is distributed along the wing span, and it appears from the curve of present weights that such distribution will be

essential in very large machines if the wing weight is not to become excessive, and that the scheme, so much favoured by the Germans during 1918, of concentrating all the power units in a central fuselage will be carried out only under a heavy penalty as sizes increase still further.

It is of some interest to compare the results given by these formulæ with those found by other investigators. The most complete wing weight formulæ previously published are those of Barnwell.* Barnwell gives a set of seven formulæ derived especially for an aspect ratio of 7.2 and for a loading of 8lbs. per sq. ft., but presented as substantially valid for other aspect ratios. Fig. 5, in which the wing weight ratios are plotted in accordance with Barnwell's formulæ and with the formula here derived (taking W/A as 8 and the aspect ratio as 7.2), shows that Barnwell's formulæ make less allowance for improving efficiency of construction with increasing size than does the writer's, and that they are palpably inapplicable to weights over 20,000lbs. For medium-sized machines the two sets of figures show reasonably good agreement and change with changing size in the same general manner, although at very different rates.

* Aeroplane Design, by Captain F. S Barnwell. "Flight," January 6th, 1921, p 13.